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A RUTILE TRAVELING WAVE MASER

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SUMMARY

This paper introduces a new type of traveling wave maser, in which the active material is chromium doped rutile (TiO_2) and the slow wave structure is a meander line. The basic components of a maser, i.e. the active material, the slow wave circuit and the reverse isolation requirements are discussed. This device has a 10°K noise temperature. Data are presented on the gain realizable over a 250 Mc tunable bandwidth.

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INTRODUCTION

The name *maser* is an acronym describing the device's operating principle: Microwave Amplification by Stimulated Emission of Radiation. The mechanics of stimulated emission was predicted by Einstein[1] in 1917; and a publication by Weber[2] in 1953 proposed that the phenomenon could be utilized as a gain mechanism. Since the conception of a practical three-level solid-state maser by Bloembergen[3], maser technology has progressed rapidly. The impetus for this accelerated research arises mainly from two characteristics of the maser: it is the most sensitive low-noise microwave amplifier available today, and it is a reliable device which can be ruggedly constructed.

Stated very briefly, the maser principle is as follows: When a paramagnetic ion is placed in a magnetic field, its electron spin systems may assume only the discrete energy states allowed by the principles of quantum mechanics. Under equilibrium conditions more electron spins will be in the lower than in the higher energy states, and to obtain maser action, this situation must be reversed. This *population inversion* is accomplished by *pumping*—that is, providing radiated energy from an external source of the proper frequency to elevate the electron spin systems in the lower energy levels to higher energy states. Such an inverted population can be used as a gain mechanism, since electromagnetic waves of the proper frequency, interacting with these excited electrons, will stimulate them to return to the lower energy levels, emitting photons of the same frequency. The latter add to the energy of the incident wave, which is thus amplified.

The most complex problem which had to be solved in the development of masers was the retention of the excited energy states, since atoms tend to return to their lowest energy states through spontaneous emission of radiation. The mechanism utilized in the microwave maser is the thermal isolation of the paramagnetic ions. At very low temperatures (e.g., that of liquid helium, 4.2°K) these ions are substantially free of thermal agitation. This effective isolation extends the time that an ion may remain in an excited state.

The first cavity masers had many disadvantages such as non-tunability, relatively poor gain stability, and the necessity of a circulator, which resulted in insertion loss before the maser and hence a higher noise figure. The traveling wave maser provides a workable solution to these problems. The first traveling wave maser (TWM) was developed by Bell Telephone Laboratories[4]. The majority of TWMs designed to date have utilized, as the active element, ruby (Al_2O_3) with an impurity doping of trivalent chromium. Many other materials have been investigated; for example, chromium-doped potassium cobalticyanide[5] and cerium-doped gadolinium ethyl sulfate[6] have operated successfully.

This paper is concerned with the active material *rutile* (TiO_2) doped with trivalent chromium as the impurity. The paramagnetic spectrum of Cr^{+++} in rutile was investigated by Gerritsen.[7] Preliminary investigations of rutile as a maser active material were carried out by Geusic[8] and continuing effort by L. Morris[9] has resulted in additional information on this material.

TRAVELING WAVE MASER, GENERAL CONSIDERATIONS

The final design of a TWM is a complex combination of the active material, the slow wave circuit, and reverse isolation to provide the desired gain and bandwidth of the maser.

Active Material

The characteristics of the active material will, to a great extent, determine the maser's performance. The most obviously significant properties are:

1. zero-field splitting (should be large);
2. spin lattice relaxation time (should be long);
3. density of spin systems (should be large);
4. recovery time (should be short).

Important properties of less obvious significance are:

5. ability to withstand multiple temperature cycling from room temperature to 4.2°K;
6. availability in reproducible crystalline orientations;
7. correct and reproducible impurity concentrations;
8. machineability to accurate dimensions;
9. chemical inertness.

Slow Wave Circuit

Amplification takes place in a TWM when the electron spin systems of the paramagnetic impurity ions in the host material are acted upon by an electromagnetic wave as it travels along a periodic structure, or *slowing structure*. Since the gain of the maser is proportional to the interaction time between the input signal and the excited spin system, the characteristics desired in the slow wave circuit should be a large amount of slowing over a wide passband.

Nonreciprocal Forward Gain

One of the most important characteristics of the TWM is the ability to obtain nonreciprocal forward gain and nonreciprocal reverse isolation. The reverse isolation must be great enough that the system will be unconditionally stable against any combination of input and output mismatch.

The transition between spin energy levels is strongly stimulated when the incident electromagnetic field is approximately circularly polarized. The propagating circuit is such that this field will have the circular polarization orthogonal to the direction of propagation. These waves exhibit an opposite sense of polarization above and below the circuit plane. Therefore, if an absorbing material of the proper polarization (a ferrite slab) is appropriately placed in this field, the backward wave is attenuated. In addition the ferrite must be of such composition and dimensions that it will "track" (that is, when the magnetic field, and hence the operating frequency, is changed, the ferrite must provide absorption of the backward wave at the new field and frequency).

Microwave Energy Source

This area of the maser is the simplest problem to solve. Analysis of the spin hamiltonian of the active material will provide the exact frequency or range of frequencies necessary for inversion of the spin system population. For rutile maser operation at 2-3 Gc this requirement is for a signal source in the 50 Gc range, which is a commercially available unit.

CHARACTERISTICS OF CHROMIUM DOPED RUTILE

Chromium doped rutile (TiO_2) is an extremely hard crystal with a tetragonal structure. Its dielectric constant is large (120 perpendicular to and 220 parallel to the C-axis at 4.2°K). When the chromium is added and the crystal annealed, the material becomes opaque and X-ray analysis is necessary to provide crystalline axis information. There are two titanium (or chromium) ions per unit cell (double ion site), and these ions are related by a 90 degree rotation about the Y-axis. Operation in this double ion site where the chromium ions in each unit cell are acted on simultaneously will result in an increase over the gain normally obtained by a factor of two.

Figures 1, 2, and 3 show the computer analysis of the spin hamiltonian of the Z, X, and Y-axis energy levels for chromium-doped rutile.[9]

One way to achieve enhanced maser performance is to increase the idler to signal frequency ratio. Since the zero-field splitting for rutile[7] is 43.5 Gc and is only 11.5 Gc for ruby, greater idler-to-signal ratios are obtainable for rutile. It is apparent from Equation 1, since the inversion ratio is a function of F_i/F_s, that higher zero splitting results in higher F_i.

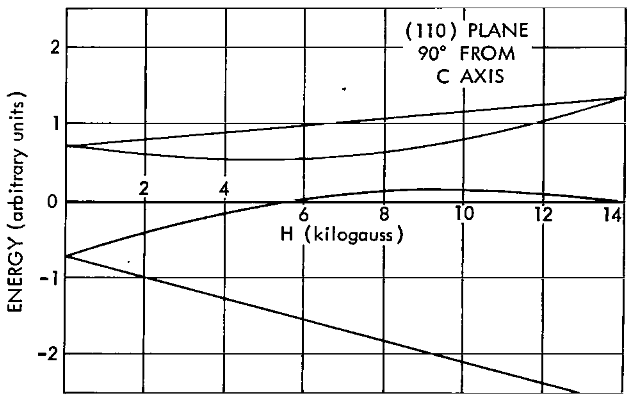

Figure 1—Z-axis energy levels for chromium-doped rutile.

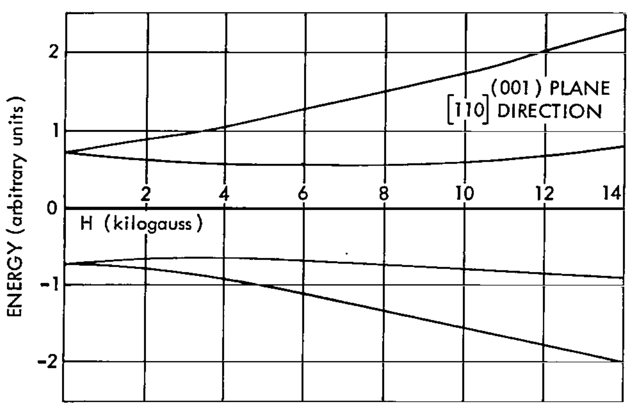

Figure 2—X-axis energy levels for chromium-doped rutile.

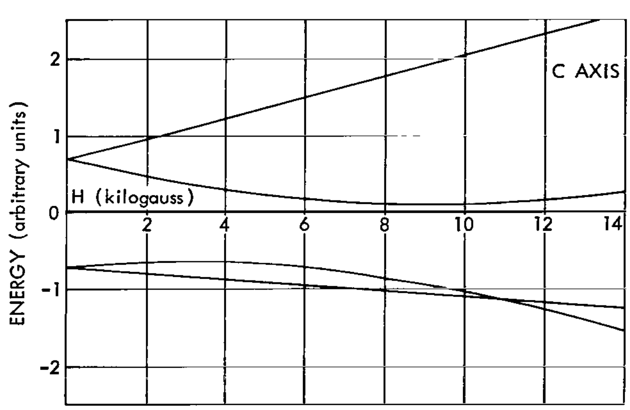

Figure 3—Y-axis energy levels for chromium-doped rutile.

The inversion ratio, which represents a positive means for evaluating maser crystal performance, is defined as the ratio of the maser's gain with the pump power applied to its absorption with the active material in thermal equilibrium. The inversion ratio takes the form

$$I = \frac{\frac{T_s}{T_i} \cdot \frac{F_i}{F_s} - 1}{\frac{T_s}{T_i} + 1} \tag{1}$$

where

T_s = signal relaxation time,

T_i = idler relaxation time,

F_i = idler frequency (pump frequency minus signal frequency),

F_s = signal frequency.

The maser gain takes the form

$$G(db) = \frac{27.3\ N\ S}{Q_m}, \tag{2}$$

where

S = slowing factor c/v_g (v_g is the group velocity of the propagating wave),

N = number of free-space wavelengths in the total length of active material, and

Q_m = $\omega(W_s{'}\ dz)/dP$ = magnetic Q of the system

or the reciprocal of the ratio of the power P emitted by the spin system in a length dz to the energy $W_s{'}$ stored per second in the length dz, for the frequency ω. The efficiency of coupling the electromagnetic energy of the traveling wave to the maser system is termed the *filling factor* and is incorporated into the term Q_m. The detailed expression for Q_m is:

$$\frac{1}{Q_m} = \frac{2\ g^2\ \beta^2\ \mu_0\ hf\ N\ \sigma_n^2\ I\ \eta}{\hbar\ KT\ n\ \Delta\ell} \tag{3}$$

$\Delta\ell$ = 3-db line width of the maser material paramagnetic absorption; this is the measured one-half value of the loss component of susceptibility.

η = filling factor,

N = spin density (spins/cm^3),

n = number of energy levels available,

I = inversion ratio,

μ_0 = permeability of free space,

β = Bohr magneton,

g = spectroscopic splitting factor,

σ_n = diagonalized portion of transition probability tensor,

K = Boltzmann constant,

T = temperature in °K,

$\hbar$ = Planck's constant/2π.

From these equations it follows that for optimum conditions the slowing should be high, Q_m should be as small as possible (the greater I the smaller Q_m), and the filling factor large. The natural 3 db line width of the maser crystal should be reasonably large to assure adequate instantaneous bandwidths. This line width criterion appears contrary to the condition that Q_m be as small as possible; however, this is overshadowed by the condition for bandwidth given by*

$$BW = \Delta\ell \sqrt{\frac{3}{G - 3}}, \tag{4}$$

where

$\Delta\ell$ = natural line width,

G = electronic gain in db.

From the foregoing equations the significance of high inversion ratios is apparent: The gain per unit length is thereby increased while the insertion loss is decreased simultaneously. This improvement can provide additional bandwidth, increased gain, reduced size, operation at elevated temperatures, or a combination of these advantages.

*This equation is derived on the basis of a Lorenzian shape of the paramagnetic absorption.

SLOWING STRUCTURE

The object of a slow wave structure in a TWM is to hold the incident microwave energy in contact with the paramagnetic ion spin system for a sufficient time to maximize the interaction of the microwave energy and the spin system. If the spin system has been elevated to the radiating state by a microwave energy source of the proper frequency, exponential gain will result along the length of the structure.

The two methods of slowing normally considered are resonant and geometric slowing. In the former, a resonant structure is utilized as a means of slowing down the group velocity. The most widely known example of this is the comb structure wherein the slowing is accomplished by forcing the normal waveguide wave to bounce back and forth many times between resonant quarter-wave fingers. Geometrical slowing in its simplest form employs a helix wherein a transmission line of length L is coiled up in such a manner that its actual length is A. In this case the wave slowing factor is L/A.

The slowing structure utilized in this maser is a meander line of 5-mil copper film (see Figure 4) which was first suggested by Siegman[9] and analyzed by Butcher[10]. This structure supports TEM waves for finger lengths of approximately quarter wavelengths. These TEM waves can be thought of as traveling back and forth along the tape at right angles to the slow wave direction of propagation. The technique thus combines resonant and geometrical slowing.

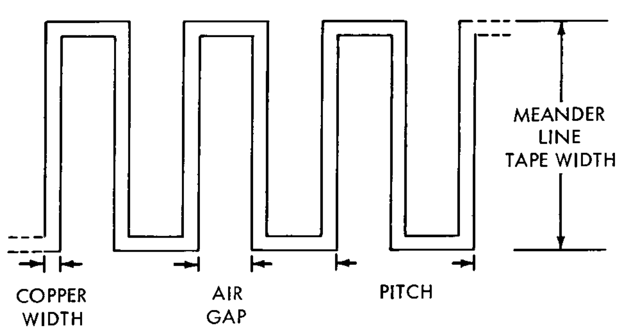

Figure 4—Meander line used as a slowing structure in the rutile maser.

The ratio of air gap width to copper width is a critical parameter for the meander line, since it determines whether the structure is geometric, resonant, or a combination. For the limiting case of narrow tape and large air gap the slowing would be geometrical, and for a very narrow air gap the result is resonant slowing. Proper design of the meander line combines both techniques, and good slowing over a wide frequency range is accomplished. By adjusting the copper-to-air-gap ratio the maximum tunable bandwidth may be achieved.

The active maser material applies a dielectric loading to the meander line and the exact analysis of slowing as a function of dielectric loading, especially for an anisotropic dielectric, is very difficult. This factor is determined empericaIly and the broadest bandwidth is achieved with a copper-to-air ratio of 1:1. By trading air for copper, the bandwidth is reduced and the slowing is increased. Therefore, the designer has four variables with which to determine the passband of the structure: (1) the copper-width-to-air-gap ratio, (2) the pitch, (3) the tape width, and (4) the dielectric loading. The latter can be present in several forms: width, thickness, and location of the dielectric with respect to the meander line.

REVERSE ISOLATION

To provide amplifier stability, some form of reverse isolation is necessary. In this device the mechanism is a thin bar of gadolinium doped yttrium iron garnet (YIG). By shaping the ferrite the resonance may be adjusted to track the same magnetic field as needed for the maser crystal. The ferrite must operate at liquid helium temperatures and possess line widths of sufficient magnitude to enable proper tracking, that is, as the operating frequency of the maser is changed by adjusting the magnetic field, the ferrite absorption resonance must follow the magnetic field and continue to provide reverse isolation. Figure 5 shows a number of cross-sectional dimensions for ferrite rods and their change in tracking[9] as the pure YIG is cooled from 290K to 77K, and then to 4.2K.

The resonant frequency of a ferrite sample is determined by the magnetic field, the inherent saturation magnetization ($4\pi\ M_s$), and the shape of the sample used. The equation describing these factors is the Kittel equation:

$$f = \gamma \left\{\left[H + \left(N_x - N_z\right)M\right]\left[H + \left(N_y - N_z\right)M\right]\right\}^{1/2} ,$$

where

f = resonant frequency (Mc),

γ = gyromagnetic ratio

H = applied dc magnetic field (gauss),

M = magnetization

N_x, N_y, N_z = demagnetizing factors

Figure 6 is a diagram based on Kittel's formula.[9] The dashed line shows the Y-axis curve for rutile. The curve is based on pure YIG (yttrium iron garnet) which has a saturation magnetization of $4\pi\ M_s = 2400$ gauss at 4.2°K. The forbidden regions indicated in the graph are regions where the ferrite sample is not fully saturated and hence lossy.

The saturation magnetization of 10% gadolinium doped YIG is approximately 700 gauss. The pure YIG saturation magnetization of 1750 gauss (both values for 4.2°K) would have been too high and resulted in an unsaturated, or lossy, mode for the lower frequencies. It can be seen from Figures 5 and 6 that 10% gadolinium doped YIG can be shaped to track rutile and hence provide the necessary reverse isolation.

OPERATING PARAMETERS

The most significant contribution of the maser is its low noise operation. This maser has a noise temperature of 10°K, of which less than 1° can be attributed to the structure. The remaining 9° is encountered in input losses.

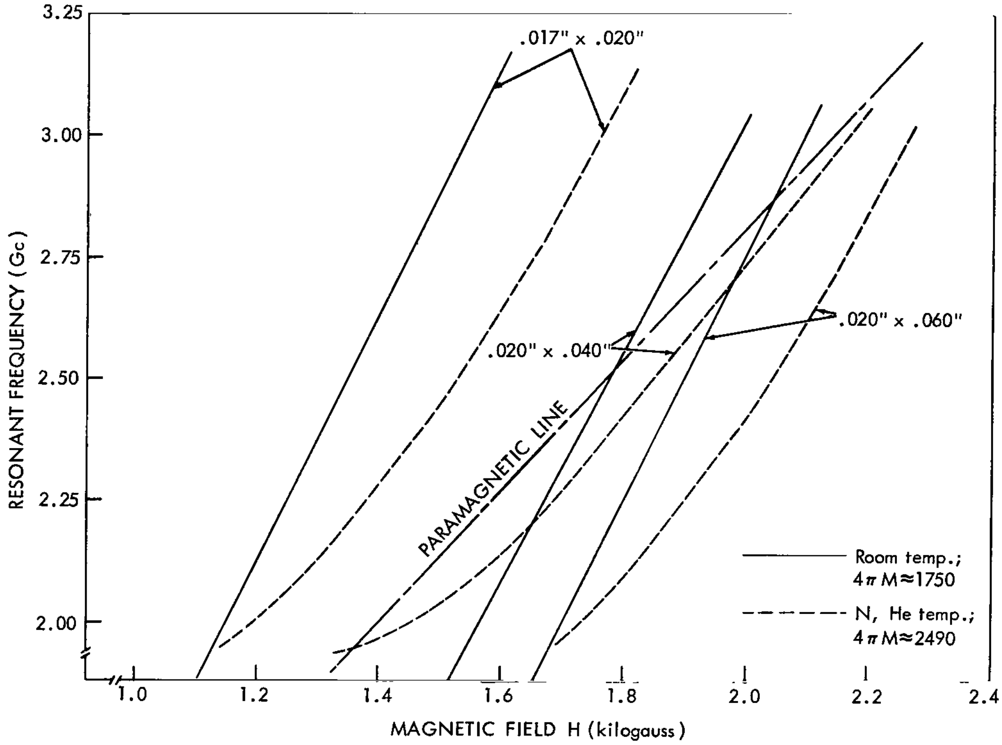

Figure 5—Ferrite "tracking" curves.

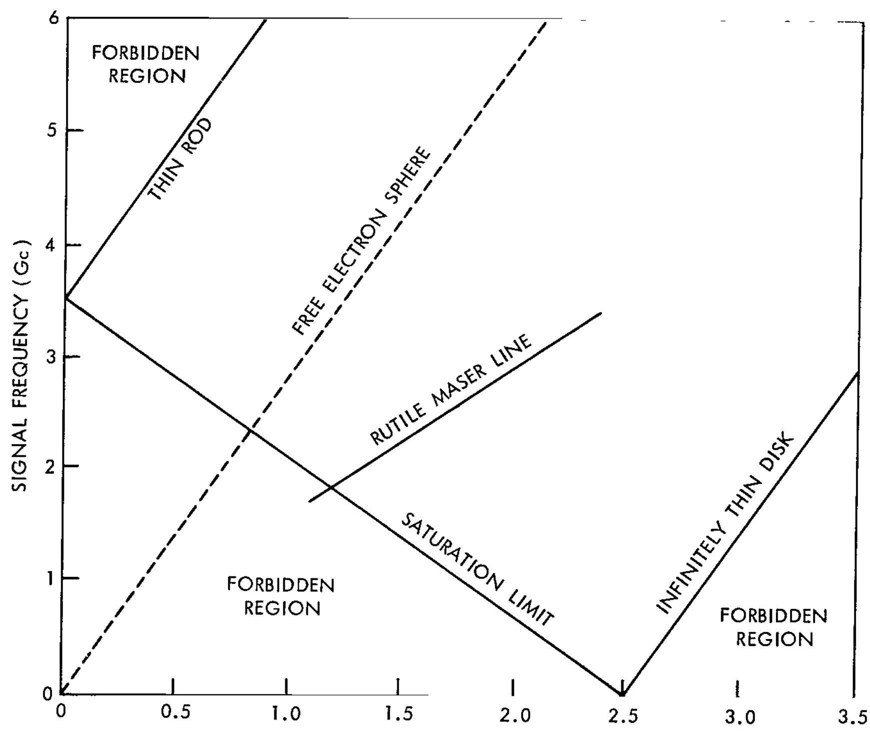

Figure 6—Plot based on Kittel's equation, for pure yttrium iron garnet (YIG) at helium temperature; $4\pi M \approx 2490$.

The magnetic fields necessary for maser operation in our frequency range (2-3 Gc) are in the vicinity of 1.5 kilogauss and the pump frequency is approximately 50 Gc.

An example of the gain data for a particular crystal orientation is given in Table 1.

Table 1

Example of Gains Obtained with the Maser with a Particular Orientation of the Rutile Active Element.

Operating Frequency (Gc)	Gain (db)
2.05	18
2.1	18
2.15	25
2.2	33
2.25	37
2.3	24

Programs presently underway include an analysis of the inversion ratio as a function of impurity concentration. In addition, magnetic shimming is being investigated in order to provide wider bandwidths. Another phase of the effort to obtain additional bandwidth is an analysis of the results of purposely misaligning portions of the active material and thereby "smearing" the energy levels over a wider range for the same magnetic field.

Experiments with a folded structure will begin soon. This structure allows the rutile to be so placed that, effectively, 12 inches of material require only 6 inches of magnetic field. Optimizing the filling factor, reducing the insertion loss, and providing simpler means of coupling in and out of the meander time with optimum VSWR are further areas under study. A future program under consideration is the evaluation of iron doped rutile as a maser material. This impurity provides spins of 5/2 and thereby two additional levels for utilization. The program will involve an impurity concentration evaluation and multiple pumping schemes.

CONCLUSION

Experimental results indicate that rutile is in fact superior to ruby as an active element. The higher inversion ratios provide higher gain per unit length which may be traded for bandwidth. Bandwidths of 200 Mc and gains of 30 db appear attainable with this material. Considerable investigation will be necessary to optimize this maser configuration and fully realize its potentialities.

(Manuscript received June 12, 1964)

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